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Studies of the Solar Wind Interaction and Ionospheric Processes at Mars and Venus.

Final Report

Andrew F. Nagy

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This is the final report summarizing the work done during the last three years under NASA Grant Grant NAG5-8946. Our efforts centered on a systematic development of a new generation of three dimensional magneto-hydrodynamic {MHD} numerical code, which models the interaction processes of the solar wind or fast flowing magnetospheric plasma with "non-magnetic" solar system bodies (e.g. Venus, Mars, Europa, Titan). We have also worked on a number of different, more specific and discrete studies, as various opportunities arose. In the next few pages we briefly summarize these efforts.

The interaction of the solar wind with "non-magnetic" solar system bodies is very different from those that have strong magnetic fields, such as the Earth or Jupiter. The obstacle to the supersonic solar wind flow is the ionosphere/atmosphere system at planets such as Mars and Venus. A contact discontinuity, called the ionopause, is formed, separating the shocked solar wind protons from the planetary thermal ions. Thus the nature of the interaction has a strong influence on the structure of the upper ionosphere, the formation of the ionopause and magnetic pile-up boundary (also sometimes called magnetic barrier). Furthermore the nature, shape and location of the bow shock are influenced by the ionosphere, upper atmosphere and exosphere of the planet. In order to achieve a thorough understanding/description of the nature and behavior of the plasma environment of these solar system bodies, we must be able to elucidate and thoroughly understand the physical processes which are responsible for and control these interactions.

The use of gasdynamic and later MHD models to study the interaction of the solar wind with the Earth began about three decades ago [e.g. *Spreiter et al.,* 1966]. Variations of these models have also been successfully applied to other magnetic planets, such as Jupiter [e.g. *Ogino et al.,* 1998; *Hansen,* 2001]. Both gasdynamic and MHD single-fluid models have also been used to study the interaction of the solar wind with the "non-magnetic" planets, Venus and Mars [e.g. *Spreiter et al.,* 1970; *Murawski and Steinolfson,* 1996; *Bauske et al.,* 1998]. More recently, a semi-kinetic model has been employed to study the solar wind interaction with Venus and Mars [e.g. *Brecht,* 1997]. These semi-kinetic model calculations have been very useful in showing the lack of symmetry in the interaction processes. It has been argued that the use of semi-kinetic models is especially appropriate for Mars, where the ion gyroradius is of the same order as the planetary radius. However, it is important to note that the ideal MHD equations have been found to be successful even in such situations. The possible reason for this maybe the fact that, as shown by the semi-kinetic code, and observed by the Phobos-2 wave instrument [*Grard et al.,* 1989], and the MGS magnetometer [e.g. *Acuna et al.,* 1998; *Cloutier et al.,* 1999], significant wave activity and turbulence are present, leading to a wide variety of wave particle interactions, which in turn act as pseudo-collisions. All the models mentioned so far have used a solid conducting sphere as the inner boundary in their formulation, even though we know that the ionosphere/atmosphere system is the actual obstacle. During the last decade multi-species and/or multi-fluid MHD models have been introduced to study these interaction processes [*Tanaka and Murawski,* 1997; *Liu et al.,* 1999a; *Sauer et al.,* 1996], providing a significant step forward in these calculations.

The Aerospace Engineering Department of the University of Michigan has among its faculty some of world's best computational fluid dynamicists. A number of years ago some of us in the planetary science and space physics community in the Atmospheric, Oceanic and Space Science Department recognized the opportunity that the presence of these individuals provided and proposed to develop multidimensional MHD codes, with an adaptively refined unstructured grid system. Significant funding was received to develop such exciting, new numerical codes for space-weather studies. This in turn led us to realize that "piggybacking" on these developments we can open the door to a new class of MHD models to study Mars, Venus and other non-magnetic solar system bodies at significantly reduced additional cost and effort. Thus we began a systematic step by step effort, which has lead to the current multi-species, 3D, MHD models, with an ionosphere and mass loading processes included.

During the last grant period we completed the development of the model which transformed it from a single to a multi-species formulation. This work was the Ph. D. dissertation of one of our graduate students, Ms. Yifan Liu [*Liu,* 2000]. This new numerical code is an extensively modified version of a numerical model, named BATS-R-US (Block Adaptive-Tree Solar-wind Roe-type Upwind Scheme) [c.f. *Powell et al.,* 1999], which is the latest version of the single-fluid MHD code developed here at Michigan, under separate NASA and NSF sponsorship. The BATS-R-US solution method is a highly scalable, massively parallel, block-adaptive mesh refinement (Block-AMR) algorithm developed for space physics applications that makes use of recent algorithmic advances in high-resolution upwind technology. The basic elements of the modified solver are: 1) a cell-centered upwind finite-volume approach that solves the hydrodynamic and electromagnetic equations in a tightly coupled manner (rather than in separate steps); 2) a flux function based on a new 9-wave approximate Riemann solver that accounts for the propagation of MHD waves in a way that is stable, accurate, and conservative; 3) limited linear reconstruction that provides second-order accuracy away from high-gradient regions and monotonic non-oscillatory solutions throughout the computational domain; 4) explicit multi-stage time stepping (source terms are treated point-implicitly); 5) block-based solution-adaptive Cartesian grid and data structure; 6) physics-based refinement/coarsening; and 7) a parallel implementation that yields extremely high computational performance on a variety of massively parallel architectures. The resulting parallel adaptive upwind solution algorithm is both robust and accurate across a wide range of values of plasma β (the ratio of thermal and magnetic pressures). The BATS-R-US numerical scheme has been described in some detail by Powell et al., [1999]. Even with the aid of solution-adaptive grids, however, resolving three-dimensional, unsteady flows requires massive computing power. This can be achieved most efficiently by employing massively parallel computers. The scheme incorporated in BATS-R-US is highly scalable, exhibiting excellent parallel performance. The code, under the HPCC umbrella, has achieved near perfect scalability and better than 344 Gflops (this corresponds to better than 20% peak performance) on a 1490-node Cray T3E. Good performance has also been obtained on SGI Origin systems and PC Beowulf clusters.

The new, modified multi-fluid version of the BATS-R-US code solves the MHD equations, in a tightly coupled manner. The relevant equations, eigenvectors, propagation speeds etc. for the multi-species model have been derived and calculated [*Liu.,* 2000], and the model has been coded for multi ion-species implementation. Continuing with our philosophy of code development, which is a step-by-step approach, first the simplest two-species version was tested and compared to the results from single fluid calculations. This multi-species code was then used to investigate the solar wind interaction with Mars [*Liu et al.,* 1999a, b, c; *Liu,* 2000; *Liu et al.,* 2001], Europa [*Liu et al.,* 2000; *Liu,* 2000] and Titan [*Liu,* 2000; *Nagy et al.,* 2001a]. A number of seminars, tutorials and papers were also given on the general subject of the interaction of rapidly flowing plasmas with non-magnetic solar system objects [e. g. *Nagy and Gombosi,* 2000; *Nagy,* 2000a; *Nagy and Gombosi,* 2001; *Nagy,* 2002]

In the current 3-species version of the model we solve the following set of MHD equations:

$$\frac{\partial \mathbf{W}}{\partial t} + \{\nabla . \mathbf{F}\}^{T} = \mathbf{Q} \qquad (1)$$

where the total energy density is defined as

$$\varepsilon = \frac{1}{2}\{\rho_1 + \rho_2\}u^2 + \frac{1}{\gamma - 1}p + \frac{B^2}{2} \qquad (2)$$

the state, flux, and source vectors in equation (1) are

$$\mathbf{W} = \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \{\rho_1 + \rho_2 + \rho_3\}\mathbf{u} \\ \mathbf{B} \\ \varepsilon \end{pmatrix} \qquad (3)$$

$$\mathbf{F} = \begin{pmatrix} \rho_1 \mathbf{u} \\ \rho_2 \mathbf{u} \\ \rho_3 \mathbf{u} \\ \{\rho_1 + \rho_2 + \rho_3\}\mathbf{uu} + \left\{p + \frac{B^2}{2}\right\}\mathbf{I} - \mathbf{BB} \\ \mathbf{uB} - \mathbf{Bu} \\ \mathbf{u}\left\{\varepsilon + p + \frac{1}{2}\mathbf{BB}\right\} - \{\mathbf{B}\cdot\mathbf{u}\}\mathbf{B} \end{pmatrix} \qquad (4)$$

$$\mathbf{Q} = \begin{pmatrix} 0 \\ S_2 - L_2 \\ S_3 - L_3 \\ \{\rho_1 + \rho_2 + \rho_3\}\mathbf{g} - \{\rho_1 + \rho_2 + \rho_3\}\nu\mathbf{u} - \mathbf{u}L_2 - \mathbf{u}L_3 \\ 0 \\ Q_6 \end{pmatrix} \qquad (5)$$

$$\begin{aligned} Q_6 = {} & \{\rho_1 + \rho_2 + \rho_3\}\mathbf{u}\cdot\mathbf{g} - \frac{1}{2}u^2\{L_2 + L_3\} - \{\rho_1 + \rho_2 + \rho_3\}\nu u^2 - \frac{1}{\gamma - 1}\frac{L_2 p}{\{32\rho_1 + \rho_2 + 2\rho_3\}} \\ & - \frac{1}{\gamma - 1}\frac{L_3 p}{\{16\rho_1 + 0.5\rho_2 + \rho_3\}} + \frac{1}{\gamma - 1}S_2\frac{k}{m_2}T_o + \frac{1}{\gamma - 1}S_3\frac{k}{m_3}T_o \end{aligned} \qquad (6)$$

and where ρ_1, ρ_2 and ρ_3 are the H^+, O_2^+ and O^+ mass densities, respectively, S_2, S_3 and L_2, L_3 are the O_2^+, and O^+ mass source and loss rates, respectively, p is the total thermal pressure of the plasma, **u** is the velocity of the plasma, ν is the ion neutral collision frequency (taken to be 4×10^{-10} {[O] + [CO2]} s^{-1}, T_o is the temperature of the newly produced ions, γ is the ratio of specific heats (and taken to be 5/3) and the other symbols have their usual definition.

The Viking 1 and 2 retarding potential analyzer (RPA) measurements [*Hanson et al.,* 1977] and subsequent theoretical models [*Chen et al.,* 1978; *Fox*, 1993] have shown that O_2^+ is the major dayside ion below about 300 km in the ionosphere of Mars and O^+ becomes important above about 200 km. Thus we selected H^+, O_2^+ and O^+ as the three ions to use in our three-species model. The chemical reactions that we considered for the production and loss of O_2^+ and O^+ ions are:

$$CO_2 + h\nu \rightarrow CO_2^+ + e \quad (7)$$

$$O + h\nu \rightarrow O^+ + e \quad (8)$$

$$CO_2^+ + O \rightarrow O_2^+ + CO \quad (9)$$

$$CO_2^+ + O \rightarrow O^+ + CO_2 \quad (10)$$

$$O^+ + CO_2 \rightarrow O_2^+ + CO \quad (11)$$

$$O_2^+ + e \rightarrow O + O \quad (12)$$

We took the photoionization rate of CO_2 and O to be $7.3x10^{-7}$ and $2.73x10^{-7}$ sec^{-1}, respectively [*Schunk and Nagy,* 2000]; these ionization rates are multiplied by cos(SZA) on the dayside, where SZA is the solar zenith angle and no ionization is assumed to be present on the nightside. The rates for the reactions shown in equations (9), (10), (11) and (12) were taken to be $1.64x10^{-10}$, $9.6x10^{-11}$, $1.1x10^{-9}$, and $7.38x10^{-8}$ cm^3 sec^{-1}, respectively [*Schunk and Nagy*, 2000]. We also made the reasonable assumption that $e \approx [O_2^+] + [O^+]$, which simplified the source term. The thermal component of the neutral atmosphere was assumed to consist of CO_2 and O; their density distribution was taken to be:
$[CO_2] = 1x10^{10}\exp\{-(z-140)/15.8\}$ and $[O] = 3x10^{8}\exp\{-(z-140)/43.5\}$
where the altitudes, z, are in km.

A computational domain defined by $-24R_M \le x \le 8R_M$, $-16R_M \le y, z \le 16R_M$, where R_M=3396 km is the radius of Mars, was used in the calculations and the inner boundary was taken to be 140 km above the Martian surface. An adapted grid consisting of 17,984 blocks and 1,150,976 computational cells was used in all of the simulations with the smallest cells having a dimension of about 53 km near the inner boundary and the largest cells, located in the nightside regions far from the planet, having a length of about 6792 km.

We considered three ion species H^+, O_2^+ and O^+, representing the solar wind and the two major ionospheric ions, respectively. The inner boundary conditions were specified as follows: $\rho_1 = 0.3\rho_{sw}$, where ρ_{sw} is the mass density of the undisturbed solar wind. This boundary condition is consistent with the expectation of very low H^+ densities in the lower ionosphere, similar to the situation at Venus [e.g. *Taylor et al.*, 1980]. The O_2^+ and O^+ densities at the inner boundary were taken to be the photochemical equilibrium value. A reflective boundary was used for **u**; this boundary condition for **u**, results in near zero velocities at the inner boundary and ionospheric velocities of a few km s^{-1} in the ionosphere, as expected, assuming Venus-like conditions [c.f. *Miller and Whitten*, 1991]. The sum of the electron and ion temperatures at the inner boundary was assumed to be 3000 °K and the pressure was set accordingly. The upstream solar wind ion and electron temperatures were set to be $5x10^4$ and $3x10^5$ °K respectively. The IMF was assumed to be a Parker spiral in the x-y plane with an angle of 56 degrees and a magnitude of 3 nT and the solar wind velocity was selected to be 500 km s^{-1}, respectively. We picked the solar wind density to be 4 cm^{-3} for the nominal case and then chose double and half of this value for high and low solar wind pressure simulations, respectively. The magnetic field, **B**, can be set to zero or any arbitrary value at the inner boundary; the choice is dictated by the specific problem one wishes to address. Arkani-Hamed [2001] developed a harmonic expansion model for the magnetic field of Mars, which matches the observations [*Acuna et al.,* 1998]. We were provided with the expansion coefficients for a 60-degree expansion [*Arkadi-Hamed*, private communication].

The work that we just completed, using the most current version of our model addressed three important issues associated with the solar wind interaction with Mars. The various results of these studies have been and will be presented at a variety of national and international meetings [*Ma et al.,* 2001; *Nagy,* 2001a; *Ma et al.,* 2002a; *Ma et al.,* 2002b; *Nagy et al.,* 2002a] and has been published [*Ma et al.,* 2002c].

We first carried out calculations for the nominal solar wind case for which we assumed no crustal magnetic field, but included a hot oxygen geocorona. The hot oxygen values were taken from the calculations of Kim et al. [1998], which are similar to the values obtained by Hodges [2000]. We selected the solar maximum values, in order to maximize the possible impact of such a hot atom corona. We assumed that the hot oxygen densities are altitude dependent, but do not change with solar zenith angle on the dayside and that they are zero on the nightside. Given that we were specifically interested in maximizing the dayside results, this assumption is reasonable. We found, within the spatial resolution that our current model allows, no meaningful changes in the dayside bowshock or ionopause locations, compared to the case with no hot oxygen present in the model. We did not include thermal or hot hydrogen in our calculations, but given the mass ratios and the relative densities [e.g. *Nagy and Cravens*, 1988], they are not believed to play an important role. In the model we consider photoionization only. It was shown by Zhang et al. [1993] that electron impact ionization may at times exceed photoionization by up to a factor of four, although Krimsky and Breus [1996] have criticized this conclusion. As we were trying to test for the "maximum" effect, in a further run we multiplied the subsolar solar cycle maximum photoionization rate of the hot oxygen by a factor of four and kept it constant (solar zenith angle independent) over the dayside. However, we still could not see any significant changes in the dayside bowshock or ionopause locations. The calculations indicated that the presence of a hot oxygen corona does not, within the resolution and accuracy of the model, lead to any significant effect on the dayside bowshock and ionopause positions, but does result in a 30% and 15% increase in the trans-terminator and escape fluxes, respectively.

Next the trans-terminator fluxes and escape fluxes down the tail were calculated. First we made these calculations neglecting the effects of the crustal magnetic field, considering nominal, high and low solar wind pressure cases. We also calculated these fluxes for the nominal solar wind case and included the effect of crustal fields. The calculated fluxes for this latter case are given in Table 1.

	Terminator Flux (s^{-1})	Escape Flux (s^{-1})
O_2^+	2.72×10^{25}	1.88×10^{25}
O^+	0.47×10^{25}	0.36×10^{25}
Total	3.19×10^{25}	2.24×10^{25}

Table 1. Calculated trans-terminator and escape fluxes for nominal solar wind parameters, and the remnant crustal fields considered.

The calculated flux values were found to be consistent with the escape fluxes of a few times 10^{25} sec^{-1}, estimated from the Phobos-2 measurements [*Lundin et al.,* 1989; *Rosenbauer et al.,* 1989] and within the calculated limiting fluxes from the dayside ionosphere of $(4.4\text{-}14.2) \times 10^{25}$ sec^{-1} [*Fox,* 1997].

Finally, we ran our numerical model to assess the effects of the crustal magnetic fields, using the nominal solar wind and atmospheric parameters, with the 60-order harmonic field model [*Arkani-Hamed*, 2001]. The calculations were carried out for the case where the location of the largest crustal field (180 longitude) was pointing sunward, and the solar wind flow direction was parallel with the equator of the planet. Figure 1 shows the calculated magnetic field and velocity components in the equatorial plane, while Figure 2 shows the same parameters in the noon-midnight meridianal plane. The color plots show the magnitude of the magnetic field and velocity components; the white lines show the field line directions and the arrows indicate the direction (not the magnitude) of the velocities. The draping of the IMF is clearly visible in the equatorial plane as indicated in Figure 1; the small "bends and kinks" are the result of the crustal fields. There also appears to be a flux rope like feature; flux ropes have been observed by the MGS magnetometer [*Vignes et al.,* 2002]. The general trend of the plasma flow is upward and toward the terminator on the dayside and either downward into the ionosphere (helping to maintain the nightside ionosphere) or down the tail (and escaping from the planet) on the nightside. Figure 2 shows the presence of closed field lines (mini "magnetocylinders"), the result of the "merging" of the crustal and IMF fields. The presence of such mini-magnetospheres have been inferred by the electron reflectometer carried aboard the Mars Global Surveyor (MGS) spacecraft [*Mitchell et al.,* 2001].

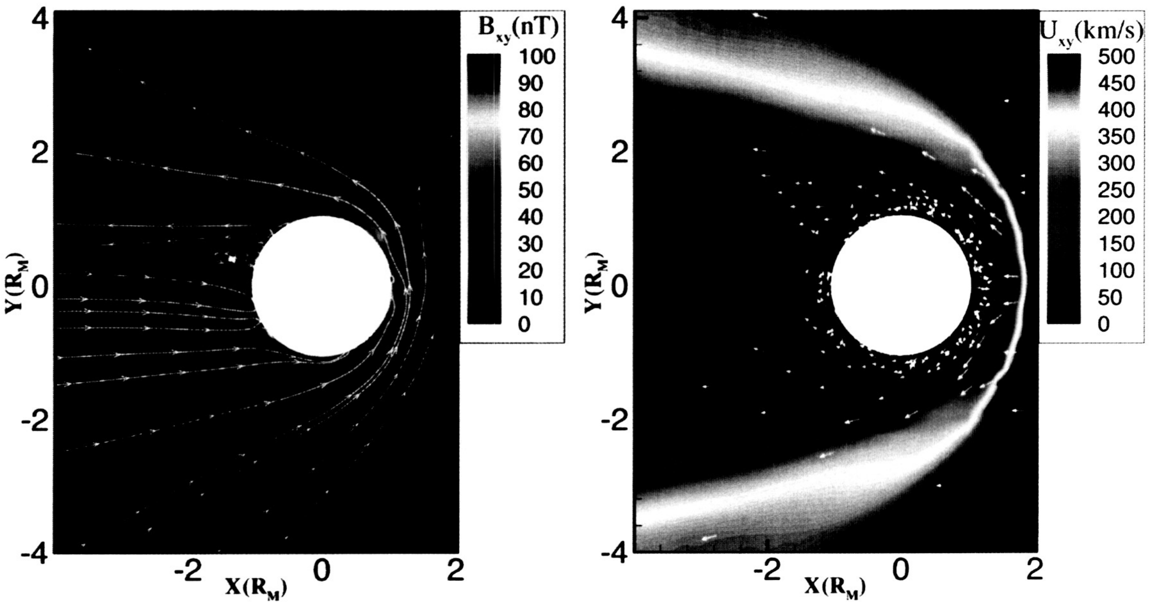

Figure 1. The component of the calculated magnetic field and velocity in the x-y plane. The color plots show the magnitudes; the white lines marked with arrows indicate the vector directions of the magnetic field and the arrows the direction (not the magnitude) of the velocity.

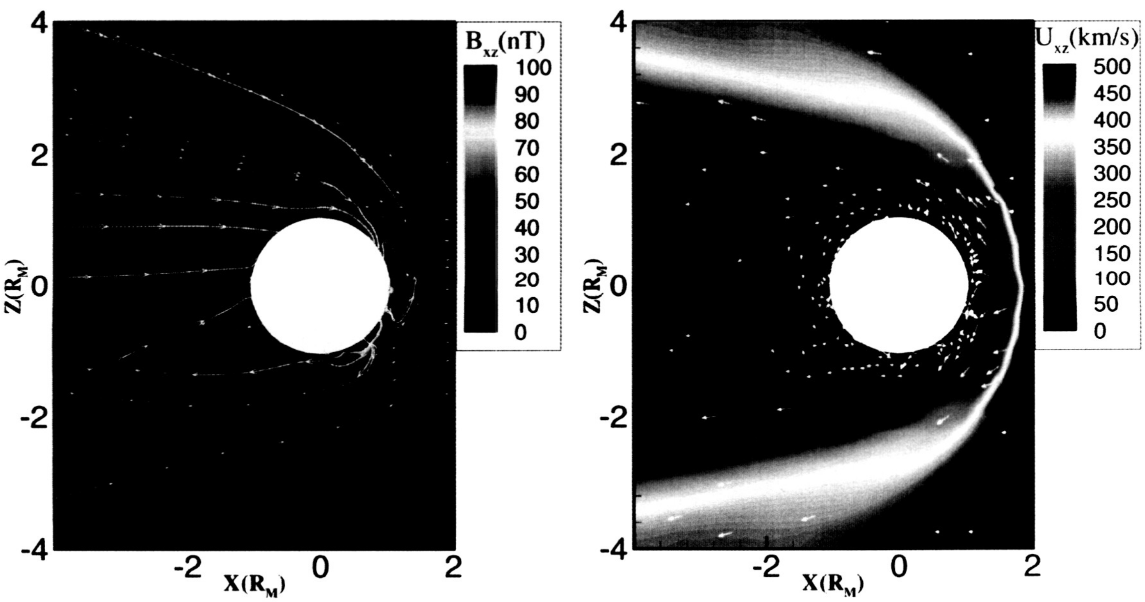

Figure 2. The component of the calculated magnetic field and velocity in the x-z plane. The color plots show the magnitudes; the white lines marked with arrows indicate the vector directions of the magnetic field and the arrows the direction (not the magnitude) of the velocity.

During the grant period a number of "studies of opportunities" were also carried out with the support of the current grant. We have worked on a variety of calculations concerning hot atom populations at Mars and Venus. The most recent effort, carried out during the current grant period, was aimed at calculating the hot carbon densities at Mars. The calculation used a two-step process: first a two-stream transport code was used to solve for the distribution function at the exobase and then these results were used in a Liouville equation solution above the exobase. It was found that photodissociation of carbon monoxide is the largest source of hot carbon atoms in the upper atmosphere of Mars, larger than dissociative recombination of CO^+ and much larger than the creation of hot carbon through collisions with hot oxygen atoms. These conclusions indicate that the situation at Mars is different from that at Venus, where the latter two processes are believed to be the dominant ones. It was also found that the high solar activity carbon densities are about an order of magnitude larger than those for the low solar activity case. The calculated values of 4.7×10^3 and 3.6×10^2 cm^{-3} near the exobase, for the high and low solar activity conditions, respectively, indicate that atomic carbon remains a minor constituent throughout the exosphere, compared to hydrogen and oxygen. These results were presented at national [*Nagy et al.,* 2000] and international meetings [*Nagy*, 2001b] and published in the Journal of Geophysical Research [*Nagy et al.,* 2001b].

We were also involved in the interpretation of the Galileo radio occultation results at Callisto. Observations of a significant ionosphere {~ 10^4 cm^{-3}} at Callisto, under certain circumstances, prompted us to evaluate its implication in terms of the presence of an atmosphere/exosphere. It was found that a detectable ionosphere was only present at the observed location when the trailing hemisphere of Callisto, which is the one that is impacted by the corotating plasma of Jupiter's magnetosphere, was illuminated by the Sun. We considered both photo and electron impact ionization, and used a couple of different approaches to estimate the surface density. It was rather surprising and reassuring to find that all of the methods used to estimate the surface neutral density gave very similar results; the estimated values fall between 1 and 3 x 10^{10} cm^{-3}. These and related radio occultation results were presented at two meetings [*Kliore et al.,* 2001a; *Kliore et al.,* 2001b] and a paper is in press in the *Journal of Geophysical Research* [*Kliore et al.,* 2002].

We were one of the three organizers of the Yosemite Meeting on "Comparative Solar System Aeronomy". The purpose of this meeting was to bring together the various communities involved in similar studies of the upper atmospheres and ionospheres of different solar system bodies. This attempt at cross fertilization of scientists, often working on similar problems and yet not aware of each other's work was highly successful. It brought together about 70 scientists and a number of graduate students with the financial assistance of both NASA and NSF. The meeting lasted 5 days and allowed a wide range of topics to be covered, including a presentation on solar system ionospheres by the P.I. of this proposal [*Nagy,* 2000b]. This meeting provided plenty of opportunities for timely interchanges among the attendants. A book, containing most of the material covered at the meeting, as well as additional related topics, has now been published

[*Mendillo, Nagy and Waite,* 2002]; this includes a chapter on solar system ionospheres co-authored by the P.I. of this proposal [*Nagy and Cravens,* 2002].

The P.I. of this proposal also participated in the international meeting "Interaction of the Solar Wind with Mars; Comparison between MGS and Phobos Results", organized and held at ISSI in Bern, Switzerland, October 22-26, 2001. The purpose of this meeting was to bring together an international community of scientists who have worked on the Phobos and MGS results, along with modelers. This was a 5-day meeting providing a platform for formal presentations [e.g. *Nagy,* 2001a] and wide ranging discussions. The meeting is being followed by the preparation of three extensive review papers and a number of contributed ones, to be published in *Space Science Reviews* and a special ISSI book. One of the review papers is "assembled" by the P.I. of this proposal [*Nagy et al.,* 2003].

In summary we supported 2 graduate students and will have presented approximately 15 papers at national and international meetings and published 8 papers in refereed journals with the full or partial support of the current grant, during its three year period.

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